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**INVESTIGATION OF AN ELECTRONIC IMAGE
ENHANCER FOR RADIOGRAPHS**

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ABSTRACT

Radiographs of nuclear and aerospace components were studied with a closed-circuit television system to determine the advantages of electronic enhancement in radiographic nondestructive evaluation. The radiographic images were examined on a television monitor under various degrees of magnification and enhancement. The enhancement was accomplished by generating a video signal whose amplitude is proportional to the rate of change of density. Points, lines, edges, and other density variations that are faintly registered in the original image are rendered in sharp relief. Examples of the applications of this mode of enhancement are discussed together with the system's dynamic response and resolution.

INTRODUCTION

The interpretation of radiographs is often difficult because even though essential details are faithfully recorded they are difficult to see because of a lack of contrast or because of excessive density. In addition, the interpreter may fail to notice or detect small grey-scale density differences. The usual methods of direct or optically-aided viewing require a high degree of eye-accomodation even with high-level backlighting. For these reasons, there is a growing effort to increase the amount of information retrievable from radiographs by means of image enhancement techniques (refs. 1 through 4). These efforts are required to make radiography a more viable and objective tool in the field of nondestructive evaluation.

Various methods of electronic image enhancement are being considered, among other techniques, for the purpose of increasing the flaw-detection capabilities of radiography. A number of enhancement techniques appear to be competitive, and there is a need to assess the relative merits and limitations of each. Therefore, the purpose of this paper is to describe results obtained at the NASA-Lewis Research Center with a video system that enhances radiographs by strongly accenting density differences. Applications of this mode of enhancement were evaluated for the purpose of indicating its value for radiographic flaw-detection and interpretation.

This report consists of two major sections. The first section describes the apparatus, theory of operation, and the inherent resolution and density response of the system. Salient features of the enhancement process are described and illustrated. The second describes results that were selected to illustrate potential applications of the system. Actual examples of the resolution and density response capability of the system are given. The major portion of the discussion is concerned with illustrative examples of the uses of the enhancement process for flaw-detection, clarification of image details, and video-metrology. Lastly, some limitations of the system are mentioned in the discussion section.

APPARATUS AND THEORY OF OPERATION

The image enhancer used for this study is a commercially-procured unit which consists of a closed-circuit television system that includes an analog computer for enhancing density increments in radiographs, figure 1. It should be noted that although radiographs were of prime interest in this study, the system is also capable of handling any photographic material.

The purpose of the apparatus described herein is primarily to aid in the location and identification of cracks and other flaws revealed by radiographs of aerospace components and test specimens. This is accomplished by electronically processing the radiographic image so that density variations indicative of cracks or inclusions, for example, are accented and displayed in a derivative television image. This particular process is termed "edge enhancement" because it makes density variations associated with edges, lines, and points stand out in a bas relief.

Figure 2 is a block diagram of the edge enhancer system. The first step in the enhancement process is to convert the original picture into a form suitable for electronic processing. This simply involves viewing an illuminated picture with a closed-circuit television camera. In the case of radiographs, a high-intensity cold light source (light box) is used to back-illuminate the transparencies. The camera converts the density values in the radiograph to an electrical video signal that may follow either the normal or enhanced video path as indicated in figure 2.

The light box can adequately illuminate transparencies having photographic density values as high as 3. The camera position is adjustable and the camera lens provides for magnification of the viewed image and for adjustment of exposure for light and dark transparencies. The resolution capabilities of the system depend on the lenses used and are limited essentially by the illumination and lens aperture.

The camera selected for the enhancer has a standard 525-line television raster and produces an effective scanning spot-size that is $1/500$ of the picture height on the camera's photosensitive target. With the 525-line scanning system, the measured resolution of the videcon tube is approximately 600 vertical lines and 500 horizontal lines. At the 525-line rate, the camera has a dynamic range of 2.4 density units which is compatible with usual radiographic densities of somewhere between 2.2 and 2.7. Our selection of a 525-line over a 1000-line scan rate involves the following considerations. If the videcon were pushed for resolution of 1000 vertical lines at the 1000-line rate, there would be a corresponding reduction in overall dynamic range from 2.4 to 1.9 density units. Moreover, the signal-to-noise ratio and contrast would be reduced appreciably.

When the signal from the video camera follows the normal video path, the image may be viewed on the television monitor as either a positive or negative reproduction. With the signal following either the normal or enhanced video path, the image may be readily magnified on the television monitor screen by up to 30X. For example, figure 1 shows a 30X magnification of a 16mm test film frame. Higher magnifications are possible but are unwarranted for most conventional radiographs.

The enhanced video path has a logarithmic amplifier that converts the camera signal to a signal that is proportional to the film density. The camera output signal, E , is given by

$$E = K I^\gamma$$

where I is the light intensity transmitted by the radiograph, γ is a constant for the videocon tube, and K is the camera sensitivity factor. The light from the light box is attenuated by the radiograph to produce an intensity, I :

$$I = I_0 T$$

where I_0 is the incident light from the light box and T is the transmittance of the film. Using these equations and the definition of density, the density, D , of the film is given by

$$D = \log \frac{1}{T} = \text{constant} - \frac{1}{\gamma} \log E$$

The output of the log-amplifier is therefore proportional to D . The edge polarity reversal circuit provides a positive or negative density signal to the edge enhancement circuit or video subtracter so that both positive or negative signals are available for the enhancement process.

The enhancement is performed by delaying the density signal and subtracting it from itself in the video subtracter in the manner indicated in figure 3. As seen in the examples of figures 4 and 5, the result of the subtraction is to produce a grey picture for large black or white areas and sharp black or white lines about edges (i.e., distinct changes in contrast). Both positive or negative radiographs or other types of transparencies are enhanced in the same way. The brightness of the lines in the enhancement is the same for edges having the same rate of change of density. This is true over the entire operating range of the logarithmic amplifier of about 2.4 density units. Conversely, the greater the rate of change of density at edges, the greater is the brightness of the edge enhancement. This is seen from examination of figure 6 which shows a neutron radiograph of a standard Image Quality Indicator (IQI) with and without enhancement. Without logarithmic conversion, edges in the darker parts of the radiograph would not be properly enhanced.

The difference signal is amplified by the subtracter to increase the sensitivity to subtle changes in density. The pseudo edge width is increased by increasing the video delay for the same purpose. The amount of amplification is set by the edge contrast control, and the brightness of the background grey level is set by the edge brightness control. The effects of increasing the edge width and contrast are seen in figure 7 which shows three different enhancements of a neutron radiograph taken for an experimental nuclear fuel element.

The normal and the enhanced picture videos are connected to the monitor by the electronic switch. This switch allows the display of either the normal or enhanced picture. Or, both the normal and enhanced pictures can be displayed simultaneously by high-speed switching pulses from the synchronizing generator. The enhanced picture is thereby displayed in a central rectangle surrounded by the normal picture, as in figure 4.

In addition to synchronizing the camera and monitor scanning systems and operating the electronic switch, the synchronizing generator also provides a reference dot-grid video signal that is added to the monitor video. The dot-grid video signal produces an array of dots on the screen, either in the central portion or over the entire picture. The dots are equally spaced vertically and horizontally to provide a reference grid for taking measurements of features in the radiographs. Thus, the enhancer system can serve as a video version of an optical comparator and with magnification as a micro-optical comparator. An example of the use of this feature is given (later in this paper).

The mode of enhancement can be varied according to the way the original picture is presented (oriented with respect) to the video camera. This is because the enhancer will not respond to edges or lines that are parallel to the raster scan lines. Hence, by rotating the light box (i.e., radiograph), one may factor-out certain edges or lines from the enhancement. For example, in figure 8, the vertical filaments (lines) of the graphite-epoxy composite shown in the radiograph vanish in the enhancement and only the 45-degree cross-ply filaments are enhanced. And, in figure 9, two different enhancements are produced from the same radiograph of a similar composite material specimen by rotating the light box 90 degrees.

RESULTS

Resolution Capabilities

In evaluating any enhancement technique for radiographs, one practical test is that of its ability to extract fine linear details. By using the standard Society of Motion Picture and Television Engineers (SMPTE) test film (see figure 1), it was shown that the enhancer readily resolves better than 60 line-pairs per millimeter at a magnification of 30X. It was demonstrated that even at magnifications between 10 and 20X, a 0.013mm (half-mil) diameter wire can be detected in a density background against which it was just barely visible by normal video viewing. This is illustrated in figure 10 which shows this size wire against a photographic density calibration strip. Also visible in the enhancement is a scratch in the calibration strip emulsion that had totally escaped notice in direct eye viewing.

One of the resolution test objects used in neutron radiography consists of a cadmium foil with a series of hexagonal holes and with each successive hole being separated by a smaller width of metal. A neutron radiograph of one such test object is shown in figure 11 with a 0.013mm (half-mil) diameter wire pressed against the negative. It is seen particularly from the enhancement that the wire is sharply resolved while the 0.013mm (half-mil) width of foil between the right-most holes in the figure is only vaguely resolved. Because the test-object radiograph is typical, it may be concluded that the enhancement system investigated has

a resolving capability that exceeds that actually encountered in conventional x-radiographs and neutron radiographs.

Typical Examples of Enhanced Images

An example of the potential usefulness of the enhancer as an aid in radiographic flaw detection is afforded by the following illustrative case. A series of 1.27cm (0.5-inch) diameter tantalum rods were machined into the low-cycle fatigue specimens shown in figure 12(a). Each specimen was made of two pieces of tantalum welded together at the center. Radiographic examinations were made to locate flaws in the welds prior to fatigue testing. A radiograph of one of the specimens appears in figure 12(b). Radiographs taken from two angles indicated an internal flaw or pipe in the weld zone. It is seen faintly in figure 12(b) while the enhancement in figure 12(c) clearly indicates the suspected flaw. Figure 12(d) is a photomacrograph of a section cut through the flawed region, and figure 12(e) is a photomicrograph of the flawed region.

Of course, careful direct examination of well-made radiographs should reveal flaws of the type mentioned in the previous paragraph. But, edge enhancement increases the probability of flaw detection since it alleviates much of the difficulty involved in searching for subtle details. Further advantages are derived from being able to continuously vary the degree of enhancement and the orientation of the image relative to the raster scan. Thus with rotation, edges or crack-like flaws that might escape notice are exposed in the enhancement.

Another case illustrates the point made in the previous paragraph concerning rotation to selectively enhance details. It also illustrates how known geometric features represented in a radiograph are rendered more clearly by edge enhancement and rotation of the image. Figure 13 shows an experimental nuclear fuel element consisting of uranium nitride pellets clad in a tantalum alloy and enclosed in a stainless steel container. Figure 13(a) reproduces the neutron radiograph of the capsule, and figures 13(b) and 13(c) are enhancements with the vertical and then horizontal edges accented in turn. Note that the line of contact between fuel pellets is readily seen in figure 13(c) but totally vanishes in figure 13(b). Figures 13(d) and 13(e) show the same capsule after rotation by about 30 degrees so that the enhancement simultaneously shows the containment surfaces (edges) and also the separations between the fuel pellets.

Another case illustrates the use of the edge enhancement process for retrieving detail from radiographs with a rather high density in some areas or with a wide range of density values. Figure 14 shows neutron radiographs and enhancements of a pair of stainless steel irradiation capsules containing uranium oxide fuel pellets. Figure 14(a) is a thermal neutron radiograph made after the UO_2 fuel had been redistributed by vapor transport under high temperature irradiation. With the high-contrast edge enhancement shown in figure 14(b), the redistribution of the fuel is revealed. That is, the enhancement is seen to reveal the inside profile of the fuel redistribution cavity. Figure 14(c) is an epithermal neutron radiograph of the same pair of capsules. Unlike the thermal radiograph of figure 14(a), the epithermal shows more of the internal fuel detail. Comparing figures 14(b) and 14(c),

it appears that image enhancement may substitute for epithermal neutron radiography which itself is a form of image enhancement. There is an economic advantage derivable from the enhancement process because epithermal radiography requires more than eight times longer exposures than thermal neutron radiography (~ 8 hours vs. < 1 hour). However, we note from figure 14(d), which is an enhancement of 14(c), that edge enhancement of epithermal radiographs also adds even more to the amount of detail that can be obtained.

A final illustrative case concerns the use of the enhancer for measuring can-to-clad gaps from neutron radiographs of experimental, doubly-contained nuclear fuel capsules. The purpose of this measurement is to follow irradiation-induced fuel swelling and consequent clad distortions after in-pile exposures. It is customary to make these measurements from the neutron radiographs with a scanning microdensitometer, reference 5.⁽¹⁾

Measurement of the can-to-clad gap with the video display is illustrated in figure 15. In figure 15(a), the reference dot-grid is superimposed on the image of the gap display on the video monitor. In this instance, the dot spacing is calibrated at 0.38mm (15 mils) and an attempt has been made to align a column of dots with one edge of the gap. As seen in figure 15(b), even this nominally high-quality neutron radiograph lacks the definition needed to locate the edges of the can-to-clad gap. Figure 15(c) shows the location of the gap in question at a lower magnification.

A similar can-to-clad gap is shown in the normal mode display in figure 16(a). The enhanced display in figure 16(b) shows not only the step in gap size but also indicates that the clad wall is apparently smoother than the stainless steel wall surface. Some capsules were cut apart, and it was confirmed that the stainless steel can's inside surface was indeed rougher (i.e., the surface finish on the stainless steel was about 32 rms versus about 16 rms for the tantalum clad surface).

Using the video system as an optical comparator at a magnification of 30X, a series of gap measurements were made and compared with those obtained with microdensitometer readings and with micrometer measurements obtained from the actual objects prior to assembly of the capsules. Typical results are shown in table I:

TABLE I
TOTAL RADIAL CAN-TO-CLAD GAP

Microdensitometer Measurement (mm)	Video Measurement (mm)	Micrometer Measurement (mm)
0.89	0.58 -- 0.61	0.564
0.74	0.56 -- 0.61	0.564
1.17	1.02 -- 1.14	1.125
1.24	1.09 -- 1.12	1.117

(1) All of the neutron radiographs presented in this report were made with the NASA-Plum Brook 60 MW reactor (See reference 5 for a description of the apparatus and procedure.

As seen from the tabulation, the video measurements generally fell between those obtained with the microdensitometer and those obtained with the direct micrometer gaging. The microdensitometer slit size was 0.025mm by 0.51mm with the 0.51mm parallel to the edges of the gap. Hence, the microdensitometer scans tended to average out some of the film graininess. On the other hand, making the measurements via the video display entailed fairing in by eye the edges of the can and clad. This was, of course, facilitated by enhancements such as that shown in figure 16(b).

DISCUSSION

With some exceptions, neither the normal nor enhanced video displays revealed details of the radiographs that could not be ultimately seen by direct-eye viewing or by means of simple optical aids. With proper back-lighting, magnification, and eye accommodation there is actually little information in well-made radiographs that escapes detection. Conversely, the video system does retrieve all details revealed by close optical examination. However, all these details cannot always be retrieved simultaneously with one setting of the enhancement controls. This is because the density response range of the system (i.e., 2.4) is not always adequate.

In all the radiographs presented herein, care was taken to insure that the normal, unenhanced version displayed on the monitor faithfully showed the particular details that were discussed. Thus, in the case of figures 7(a) and 12(b), the slot and flaw highlighted by edge enhancement are apparent even in the normal views. However, in figure 7, for example, other image details had to be sacrificed in order to show the slot clearly and to photograph it from the monitor screen. Nevertheless, these other details, as for example the tungsten springs in figure 7, show up clearly in the enhancement regardless of the normal display-mode density and contrast settings.

A problem that is aggravated by edge enhancement arises from film artifacts, such as the presence of defects in the film emulsion, graininess, scratches, water marks, dust, lint, etc. All these are, of course, enhanced along with other image details. In most instances, such artifacts that appear in the enhancement can be readily identified and ignored, as in conventional radiographic examinations, after a little experience is gained in interpreting the enhanced images.

Overall, the video system proved to be a valuable tool for the examination of radiographs. Its limitations are generally overcome by the benefits derived from being able to magnify, display, and electronically-enhance images for advantageous viewing.

CONCLUDING REMARKS

This paper describes an electronic image-enhancement technique that was found to be a useful tool for aiding the eye in the appreciation of subtle but important details that exist in radiographs. The image enhancement system described herein substantially reduced the demands on visual acuity and presented, on demand, various analogs of the original radiographs examined from which the eye could comfortably,

conveniently, and accurately select relevant information. This could be accomplished in real-time while the radiograph was being manipulated to expose different regions of interest.

Over 100 samples of radiographs of nuclear and aerospace components were examined and interpreted with the aid of the enhancer. Each was found to contain some detail that was either missed or difficult to see without enhancement. In general, electronic enhancement via the closed-circuit video system proved to have distinct advantages that complement the other methods for examining and interpreting radiographs; e.g., direct visual, optically-aided visual, photographic reprocessing, and microdensitometry. If for no other reason than that of providing a convenient means for enlargement, the video system was found superior to direct or optically-aided viewing methods.

The system was particularly useful for accenting points, lines, and edges that were seen only as subtle density variations in the original radiographs. It was also discovered that measurements could be made with the system that compared quite well with those made with scanning microdensitometer on neutron radiographs.

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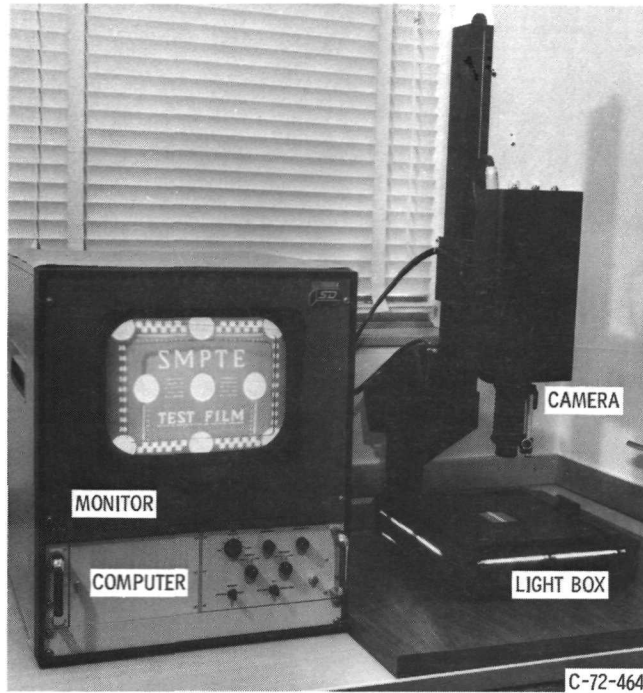


Figure 1. Image enhancer.

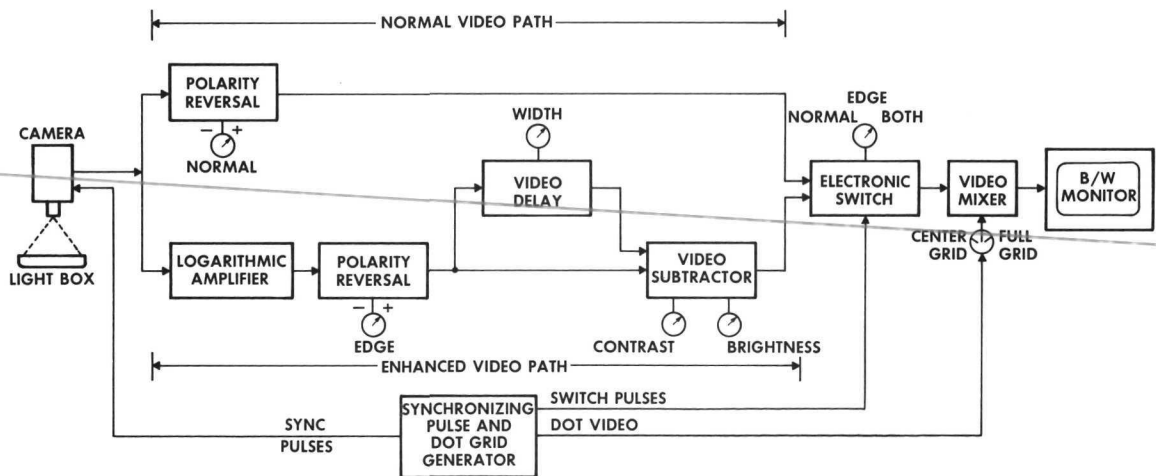


Figure 2. - Edge - enhancer block diagram.

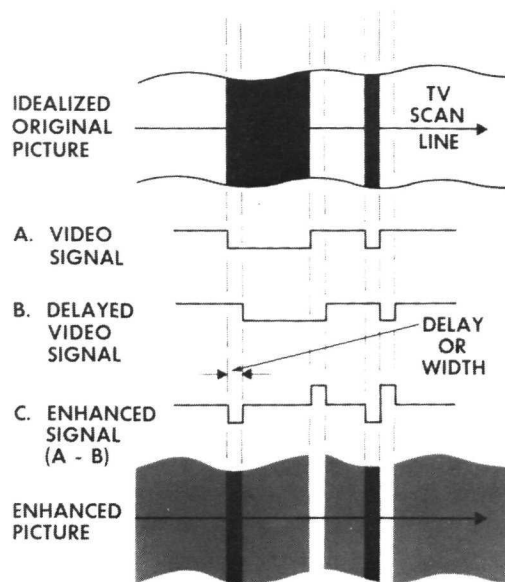


Figure 3. - Edge enhancement process.

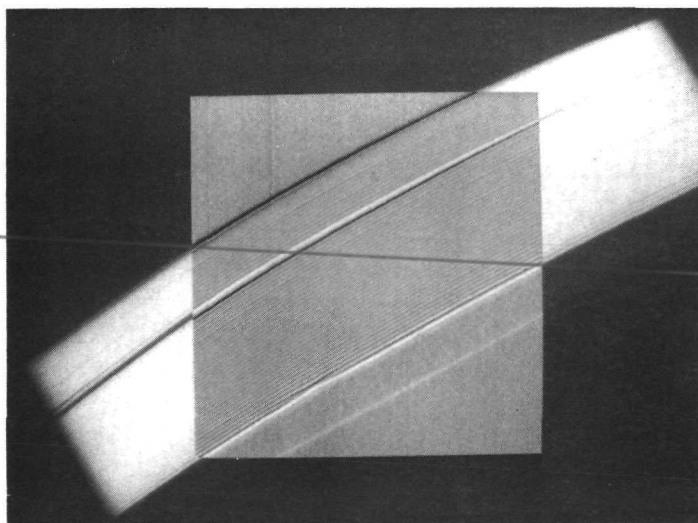
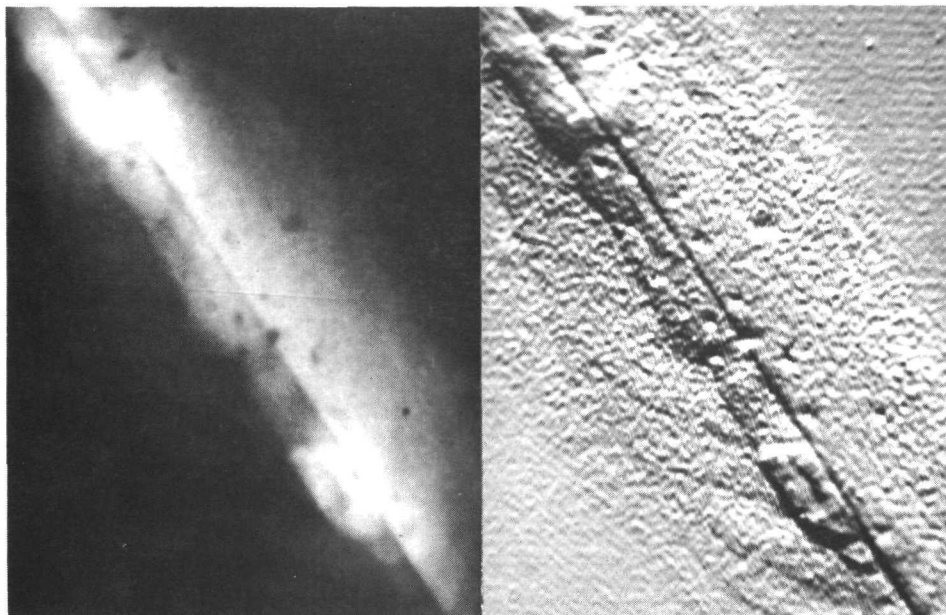


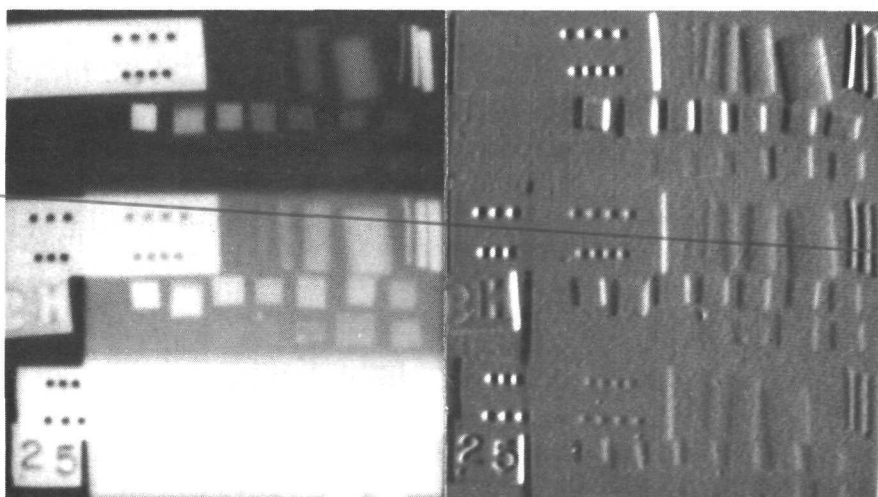
Figure 4. - Radiograph of tungsten wire clad in nickel with center portion enhanced.



NORMAL

ENHANCED

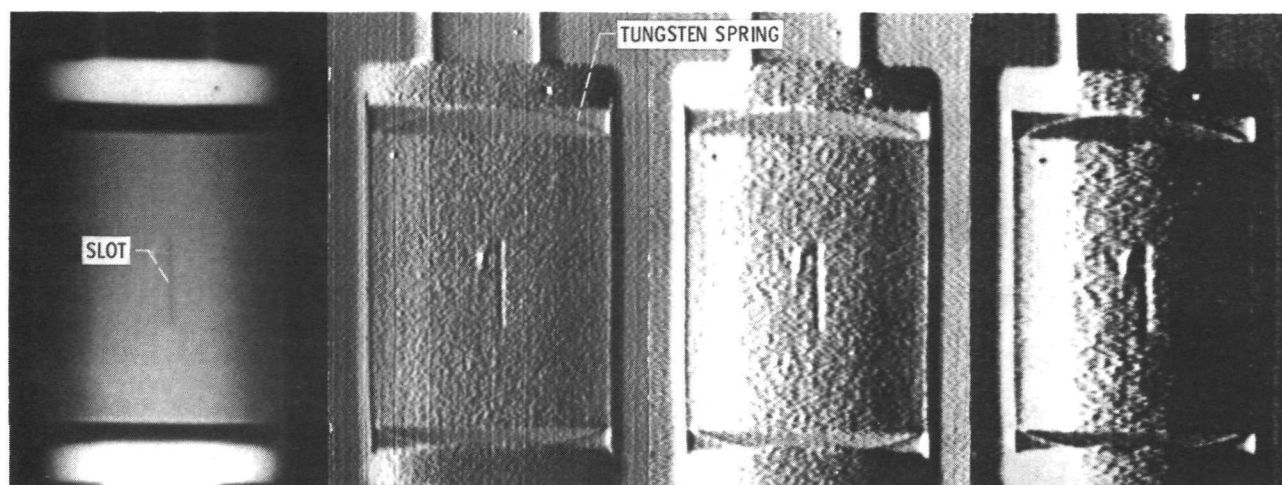
Figure 5. - Edge enhanced radiograph of weld with misalignment and inadequate penetration.



NORMAL

ENHANCED

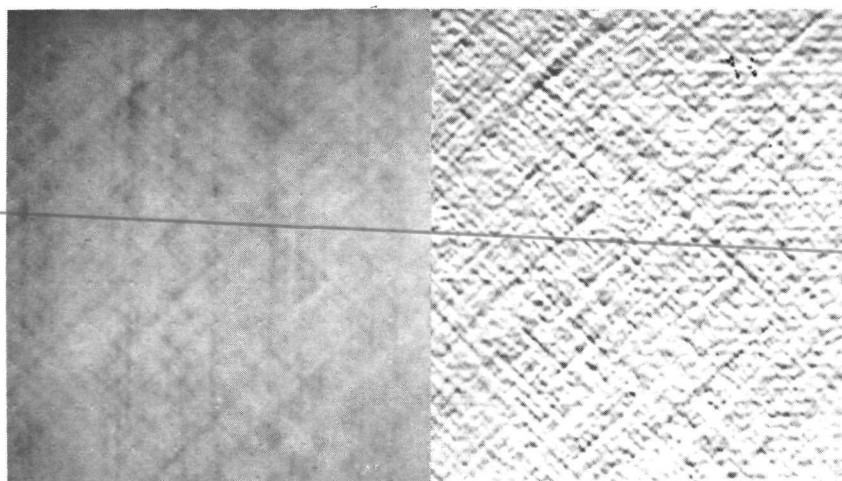
Figure 6. - Enhancement of neutron radiographic IQI.



NORMAL

INCREASING ENHANCEMENT → EDGE WIDTH AND CONTRAST

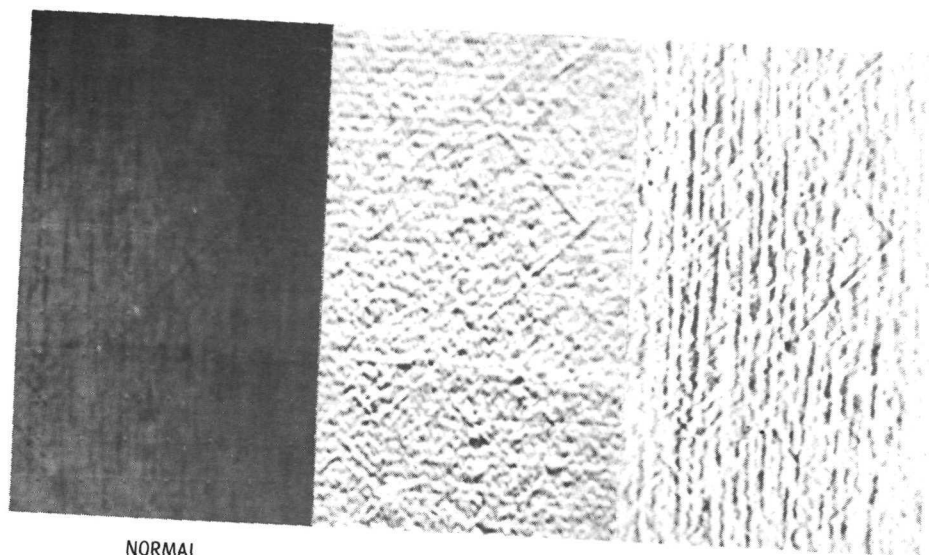
Figure 7. - Radiograph of experimental nuclear fuel capsule with artificial defect in cladding. (Fuel is cylindrical UN pellet. Cladding is tantalum alloy can with 0.076 mm (3-mil) wide eloxed slot.)



NORMAL

ENHANCED

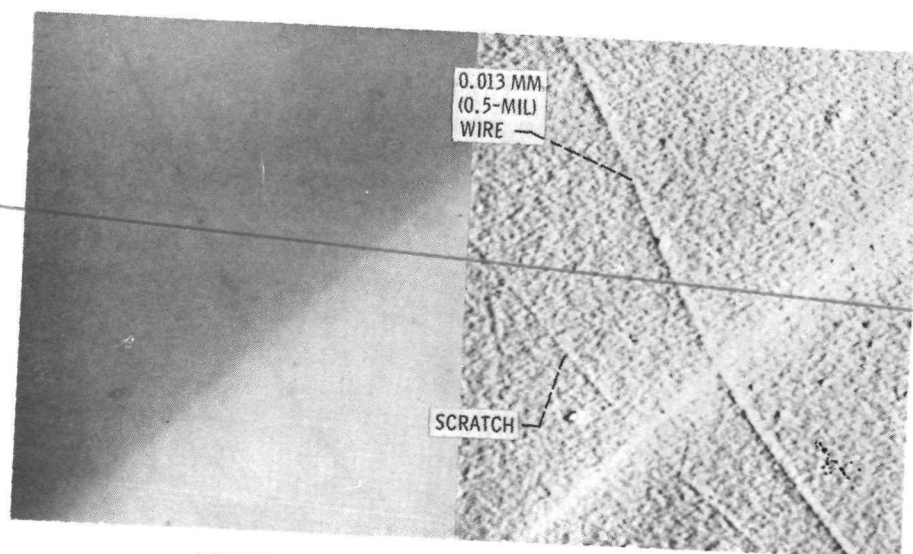
Figure 8. - Enhancement of cross ply laminations only in radiograph of graphite epoxy composite.



NORMAL

ENHANCEMENTS

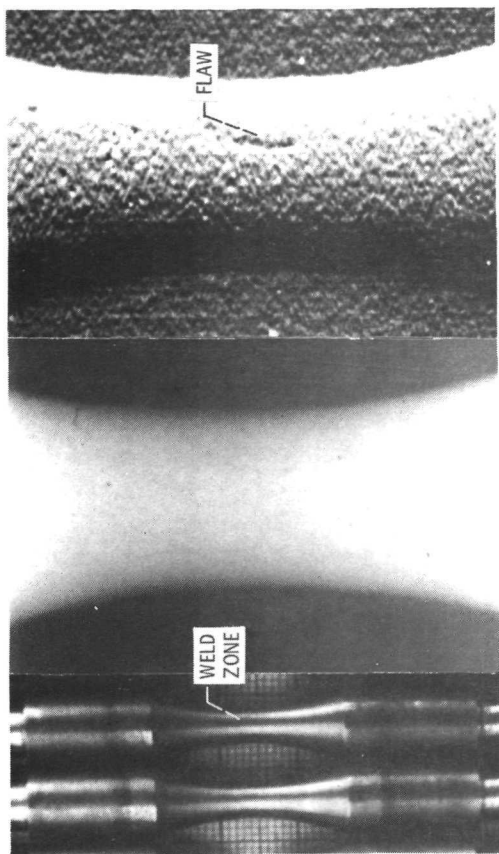
Figure 9. - Horizontal and vertical enhancements of radiograph of composite structure.



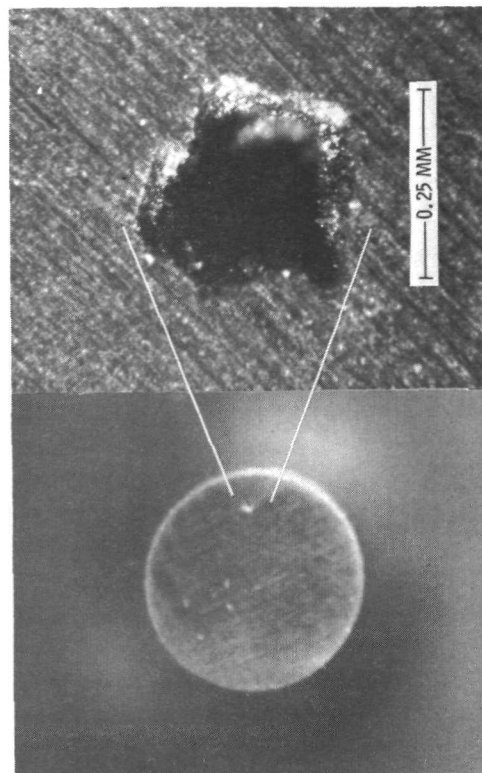
NORMAL

ENHANCED

Figure 10. - Enhancements of artificial defects for resolution test of enhancement system.



(A) FATIGUE SPECIMENS. (B) NORMAL RADIOGRAPH. (C) ENHANCED RADIOGRAPH.



(D) SECTION THROUGH WELD ZONE. (E) PHOTOMICROGRAPH OF FLAW.

Figure 12. - Fatigue specimen with internal flaw.

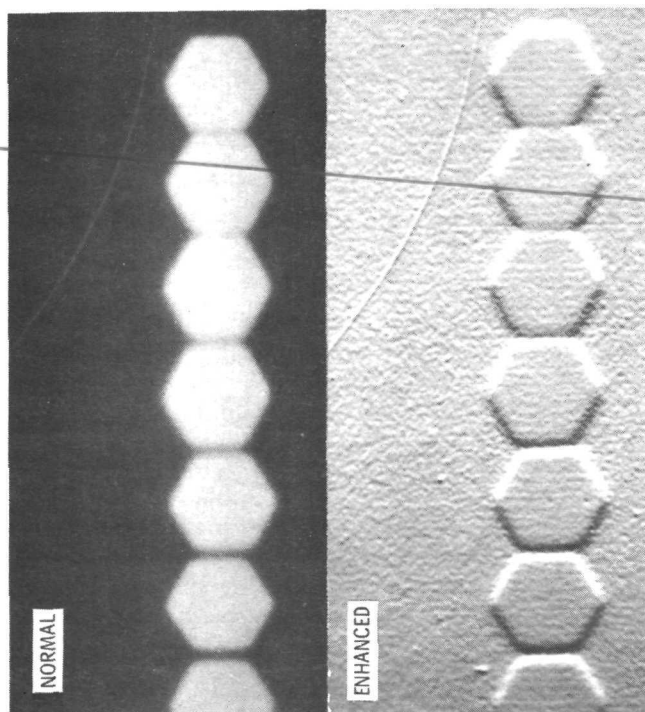
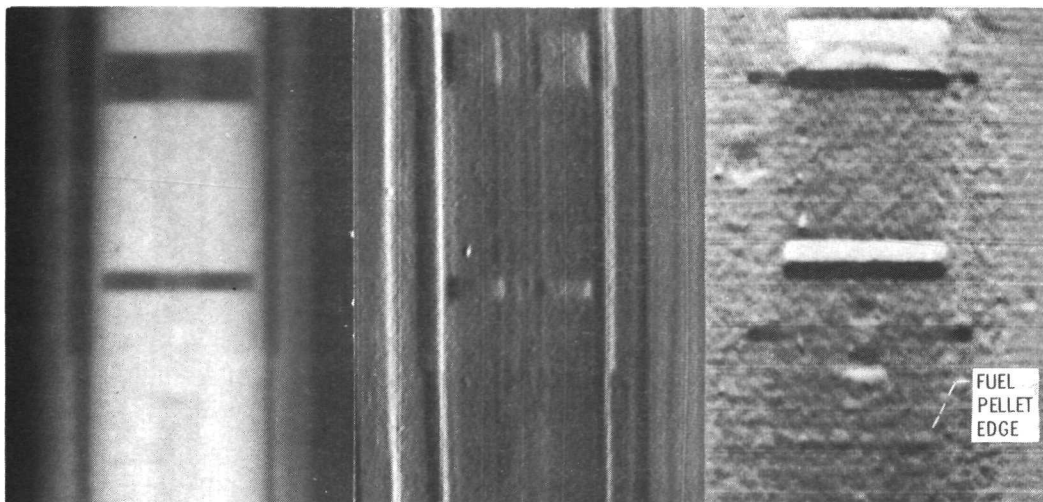


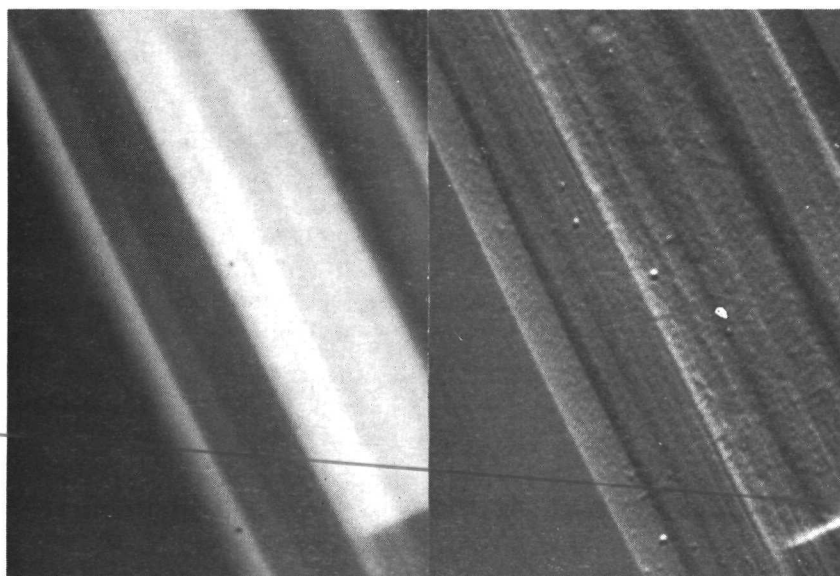
Figure 11. - Neutron radiograph of resolution test object and superimposed 0.013 mm (0.5-mil) wire.



(A) NORMAL NEUTRON RADIOGRAPH.

(B) VERTICAL EDGES ENHANCED.

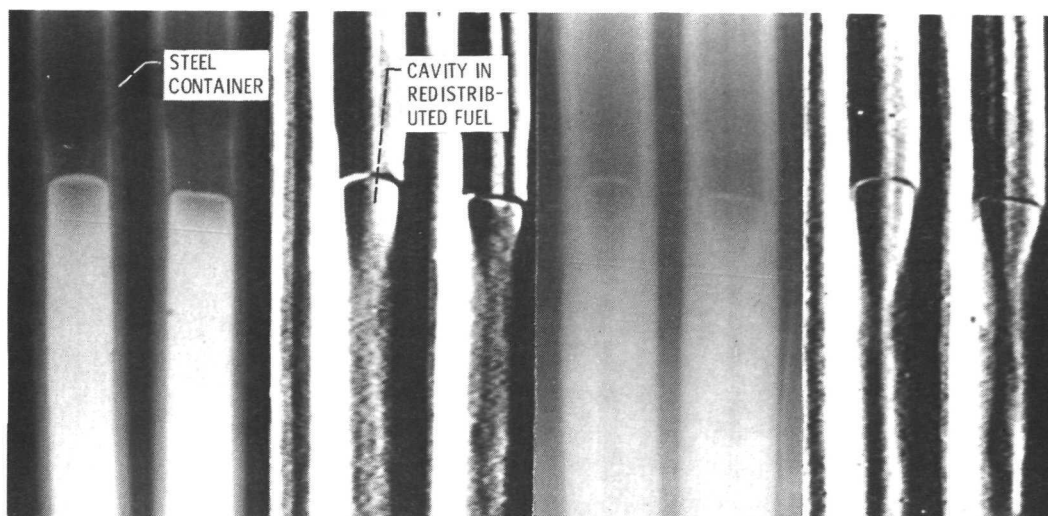
(C) HORIZONTAL EDGES ENHANCED.



(D) NORMAL RADIOGRAPH: OBLIQUE TO RASTER
SCAN LINES.

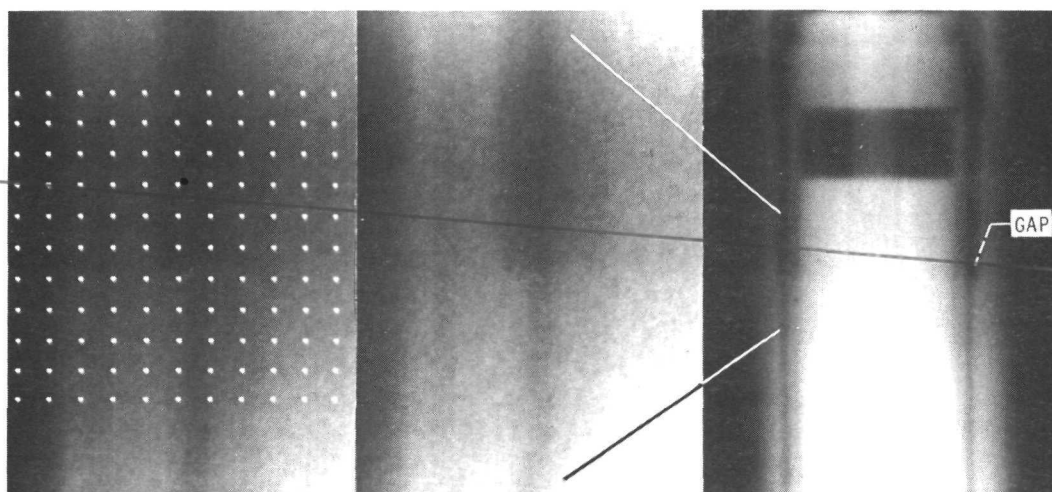
(E) VERTICAL AND HORIZONTAL EDGES BOTH
ENHANCED.

Figure 13. - Vertical, horizontal and oblique enhancements of experimental nuclear fuel element.



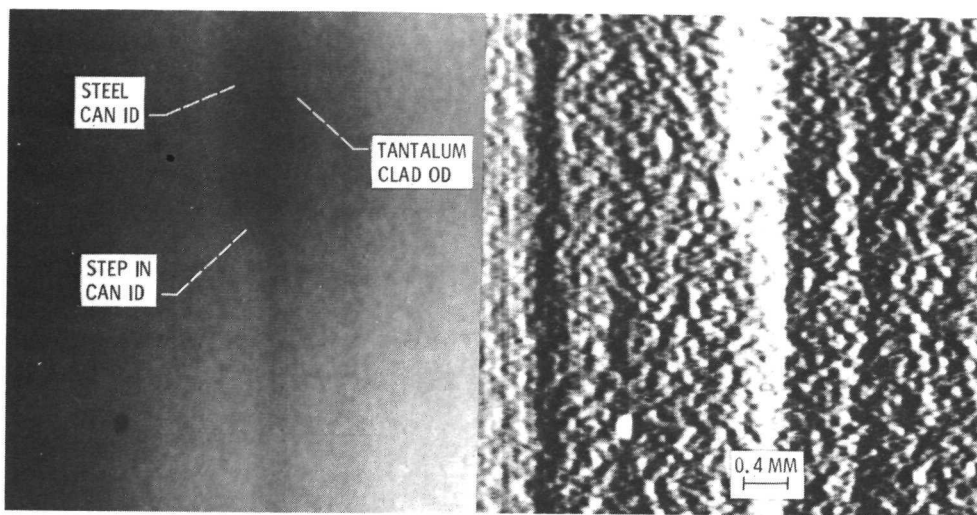
(A) NORMAL THERMAL NEUTRON RADIOGRAPH. (B) ENHANCED THERMAL NEUTRON RADIOGRAPH. (C) NORMAL EPITHERMAL NEUTRON RADIOGRAPH. (D) ENHANCED EPITHERMAL NEUTRON RADIOGRAPH.

Figure 14. - Enhancement of fuel redistribution profile in experimental fuel capsule.



(A) CALIBRATED GRID SUPERPOSED ON GAP IMAGE. (B) MAGNIFICATION OF GAP IMAGE. (C) NORMAL DISPLAY OF CAN-TO-CLAD GAP.

Figure 15. - Radiograph of experimental fuel element for measurement of can-to-clad gap.



(A) MAGNIFIED NORMAL DISPLAY.

(B) MAGNIFIED ENHANCED DISPLAY.

Figure 16. - Enhancement of experimental fuel element can-to-clad gap.